Nuclear Weapons Stockpile Stewardship

Lawrence Livermore National Laboratory was established in 1952 to help ensure national security through the design, development, and stewardship of nuclear weapons. National security continues to be the Laboratory's defining responsibility. Livermore is one of the three national security laboratories that support the National Nuclear Security Administration (NNSA) within the Department of Energy (DOE).

Livermore plays a prominent role in NNSA's Stockpile Stewardship Program for maintaining the safety, security, and reliability of the nation's nuclear weapons. The Stockpile Stewardship Program integrates the activities of the U.S. nuclear weapons complex, which includes Livermore, Los Alamos, and Sandia national laboratories as well as production sites and the Nevada Test Site. As the nuclear weapons in the stockpile continue to age, Laboratory scientists and engineers are challenged to ensure the weapons' performance and, as necessary, refurbish them or provide reliable replacements without conducting nuclear tests.

Working with the other NNSA laboratories, Livermore is attending to the immediate needs of the stockpile through assessments and actions based on a combination of laboratory experiments and computer simulations of nuclear weapon performance. In addition, the Laboratory is acquiring more powerful experimental and computational tools to address the challenging issues that will arise as the nation's nuclear weapons grow older. These vastly improved scientific capabilities will contribute to NNSA's goal of transforming the nuclear weapons complex, making it more responsive to the need for a smaller 21st century stockpile that is even safer, more secure, and easier to maintain.

Annual Assessment of the Stockpile

Livermore is a key participant in formal review processes and assessments of weapon safety, security, and reliability. In 2005, the Laboratory met all milestones in support of the tenth cycle of the Annual Assessment Review. First mandated by the President in 1995, this annual review of the stockpile is now required by law. The review assesses the current status of the stockpile and provides the President an informed judgment of whether a resumption of underground nuclear testing is warranted to resolve any issues about the reliability or safety of weapons. The formal process is based on technical evaluations made by three national laboratories and on advice from the secretaries of Energy and Defense, the three laboratory directors, and the commander-in-chief of Strategic Command.

Secretary of Energy Samuel W. Bodman, who signs the Annual Certification letter to the President, visited the Laboratory in August to learn more about programs and talk to employees.

Lawrence Livermore and Sandia prepare Annual Assessment Reports for each of the nuclear weapons systems for which the two laboratories are jointly responsible: the W62 and W87 intercontinental ballistic missile (ICBM) warheads, the B83 strategic bomb, and the W80 and W84 cruise missile warheads. As input to the reports, Laboratory scientists and engineers collect, review, and integrate all available information about each weapon system, including physics, engineering, chemistry, and materials science data. This work is subjected to rigorous, in-depth intralaboratory review and to expert external review, including formal use of red teams. Weapons experts from Livermore also provide peer review for the Annual Assessment Reports prepared by Los Alamos and Sandia for the weapon systems under their joint responsibility.

Quantifying Uncertainties in Performance

For the Annual Assessment Review, formal certification of refurbished warheads, and resolution of issues arising about deployed systems, Laboratory scientists and engineers depend on an extensive range of aboveground testing, vastly improved simulation capabilities, and the existing nuclear test database. This information is essential input into a methodology called quantification of margins and uncertainties (QMU), developed by Livermore and Los Alamos. QMU serves as a formal framework to underpin evaluations of weapons performance and technical decisions about refurbishing weapons or providing reliable replacements. The methodology, which entails the development and application of a rigorous set of quantitative standards, is analogous to the use of engineering safety factors in designing and building a bridge. For every functional requirement, the performance margin is quantified (i.e., how far is the system performance from failure) and compared to the uncertainty in the estimate of that margin (i.e., how uncertain are the estimates of performance and the point of failure).

QMU is being strengthened by research directed at reducing key uncertainties, and in one important area of weapons performance, scientists made a significant breakthrough in 2005. Laboratory researchers proposed a resolution to the energy balance issue, a 40-year-old anomaly in nuclear test data that previously could not be explained. Because of the anomaly, an ad hoc calibration had to be added to computer simulations of specific weapon systems to match the results of underground tests. Until now, the search for a physics-based model to replace the calibration had failed due to the complexity of the physics and limited computational and experimental capabilities. Based on results from recent high-fidelity, non-nuclear experiments, the availability of superior simulation tools, and careful re-examination of archival nuclear test data, Laboratory scientists developed a consistent, science-based explanation for the anomaly. Future experiments at the National Ignition Facility (NIF) will serve to confirm the work. A self-consistent physics foundation for explaining energy balance is now part of the QMU methodology. The result is reduced uncertainties when evaluating the performance of stockpiled weapons, life-extension modifications, and options for reliable replacement warheads.

As Livermore and Los Alamos continue to refine QMU, the methodology is being widely implemented in warhead assessment activities. The QMU approach was first applied in Livermore's certification of the design changes to refurbish and extend the life of the W87 ICBM warhead. Today, the methodology serves as the basis for Livermore's certification plans for extending the life of the W80 warhead (see below). In addition, QMU is supporting Livermore's activities for the Reliable Replacement Warhead feasibility study and peer review of Los Alamos' work on the W76 and W88 submarine launched ballistic missile (SLBM) warheads.

Life Extension of the W80 Cruise Missile Warhead

The Laboratory is on schedule in meeting key (Level Two) milestones in the W80 Life Extension Program (LEP). NNSA and the Air Force are pursuing the LEP to refurbish W80 cruise missile warheads, which first entered the stockpile in 1981. The refurbishment work will be carried out at NNSA production facilities based on engineering designs developed and certified by Lawrence Livermore and Sandia-California national laboratories. The program has moved from Phase 6.3 (engineering development) to Phase 6.4 (production engineering) after successful completion of two major reviews. The first review was the Phase 6.3 to 6.4 Interlaboratory Peer Review conducted by Los Alamos. Second, in early fiscal year 2005, the Department of Defense completed its Preliminary Design Review and Acceptance Group Review. Production preparations are ongoing, with numerous engineering releases sent to the production plants to support First Production Unit dates for components.

An extensive program of experimental and computational activities is under way to support the W80 LEP, executed according to the QMU approach. Laboratory scientists and engineers have performed high-resolution, two- and three-dimensional computer simulations to design and test new components, predict system performance, and prepare for certifying proposed modifications to the weapon. The simulations have also assisted in the preparation of experiments, which, in turn, provide data to compare with model predictions. All planned engineering-development experiments to validate and improve models for the modified W80 design (the W80-3) were completed in 2005. These included integrated (large-scale) hydrodynamics experiments, focused (smaller-scale) hydrodynamic tests, and relevant high-energy-density physics experiments at the University of Rochester's OMEGA laser. As production activities progress and mature, a new phase of qualification experiments will begin. They will demonstrate that the hardware from the production facilities performs as designed.

Technicians attach instrumentation to the exterior of a W80 Environmental Test Unit.

W80 Environmental Test Unit installed in an Advanced Cruise Missile in preparation for flight test FTU-1, flown in September.

Hydrodynamic tests, such as the ones performed as part of the W80 LEP, are a particularly important part of the Stockpile Stewardship Program. In some of the large-scale tests—called Integrated Weapons Experiments—scientists study the performance of mock weapon primaries as their pits are imploded by high explosives. Smaller-scale Focused Experiments, performed to study specific physics or engineering issues, are also an essential feature of the Stockpile Stewardship Program. Altogether, Livermore fired 7 Integrated Weapons Experiments and 45 Focused Experiments for the weapons program in 2005. Over the past two years, the cost effectiveness of hydrodynamics testing for the weapons program has increased by more than 100 percent as measured by the number of tests per dollar. This increased productivity resulted from an improved approach to planning and executing hydrodynamic tests. The goals were to maximize return-on-investment in the data gathered and continually improve testing, based on feedback from experimental teams.

Livermore, Sandia, and the Air Force also are performing flight tests for the W80-3. Excellent quality data were obtained in all five captive-carry flight tests, flown between February 2003 and July 2005. Captive-carry experiments mount an instrumented W80 test warhead into either an Air Launched Cruise Missile (ALCM) or an Advanced Cruise Missile (ACM) and then fly an extended B-52 mission to measure all aspects of the thermal and structural flight environment envelopes. The first free-flight test of the W80-3 was flown in September 2005 on an ACM. This test confirmed key design input requirements, such as the ejection shock level when the cruise missile is explosively separated from the B-52 bomber.

With flight and ground environment data measured, a major development ground test with the latest W80-3 hardware, called the Full System Engineering Test (FSET), began in late 2005. The flight program information provided much of the required thermal and mechanical shock and vibration conditions that FSET uses to qualify the new W80-3 warhead design. These extensive tests take over a year to complete, and they provide confidence in the future certification of the W80-3.

Dedicating Two of the World's Fastest Supercomputers

The Laboratory celebrated the tenth anniversary of NNSA's Accelerated Strategic Computing Initiative with a ceremony in October. Speakers included Ambassador Linton Brooks, NNSA administrator; Ray Orbach, director of the DOE Office of Science; and Nicholas Donofrio, IBM executive vice president for innovation and technology. Now known as the Advanced Simulation and Computing (ASC)

Program, this ambitious effort was launched in 1995 to achieve a million-fold increase in computing capability. The goal was a supercomputer that could operate at 100 trillion operations per second (100 teraops), estimated to be the minimum capability for modeling the full performance of a nuclear weapon in three dimensions with sufficient resolution. Dedication of the 100-teraops ASC Purple and the even faster BlueGene/L machines at the ceremony marked the outstanding success of ASC. NNSA and DOE are strongly committed to continuing to push the frontiers of high-performance scientific computing in partnership with U.S. industry. Both ASC Purple and BlueGene/L reside in the newly constructed Terascale Simulation Facility (see p. 36).

The ASC Purple computer system was delivered from IBM, installed, and tested in 2005. With more than 12,000 next-generation IBM Power5 microprocessors, 2 million gigabytes of storage, and 17,000 cables totaling 140 miles, ASC Purple is an enormous machine with the computing capacity of 25,000 high-end personal computers. Operation of the computer and cooling system requires 7.5 megawatts of electric power, equivalent to the usage of about 7,500 average homes. In spring 2006, the classified Purple system (1,423 nodes and 93.4 teraops) will first become available for production runs of classified problems, which can take weeks to complete. Purple will be used to run the most demanding three-dimensional weapons simulation codes with high-fidelity physics models. The unclassified uPurple system (109 nodes, 6.6 teraops) will become available at the same time for unclassified science runs.

Sitting at the number-one spot on the Top500 List of the world's fastest supercomputers is BlueGene/L. With delivery from IBM of the final 32 of 64 racks in summer 2005, BlueGene/L clocked an astonishing 280.6 teraops on the industry-standard LINPACK benchmark. Each rack is a single air-cooled cabinet with 1,024 nodes (2,048 processors). With its 65,536 nodes and system-on-a-chip technology, BlueGene/L is a world apart from other scalable computers not only in terms of performance but also in size, cost, and design. Livermore computer scientists and collaborators successfully integrated the machine into the Laboratory's computer infrastructure during the year. The endeavor entailed developing software for the control system, resource manager, job scheduler, debugger, and parallel file system. Running scientific problems in the first half of the year helped the system integration effort by revealing issues that had to be resolved. These runs also produced first-time results on important molecular dynamics problems.

One breakthrough three-dimensional molecular dynamics calculation performed on BlueGene/L won the 2005 Gordon Bell Prize, which is awarded to innovators who advance high-performance computing. A Livermore-IBM team of scientists ran a newly developed three-dimensional molecular dynamics code at a sustained speed of about 100 teraops to study the solidification of tantalum and uranium. In the 2-million-atom simulation, molten tantalum at 500 kelvins was compressed, and scientists examined the process of solidification, from nucleation to growth to grain-size structures. The 30-hour

NNSA administrator Linton Brooks, then-Laboratory director Michael Anastasio, IBM executive vice president Nicholas Donofrio, and DOE Office of Science director Ray Orbach (right to left) attend ceremonies to mark the tenth anniversary of the Accelerated Strategic Computing Initiative.

Breakthrough materials science simulations won the prestigious Gordon Bell Prize.

computer run simulated about 0.75 nanosecond—long enough to study the physics. The behavior of metals under high pressures and temperatures is an important issue for stockpile stewardship. Several other finalists for the prestigious Gordon Bell Prize entered work also performed on BlueGene/L.

Understanding Plutonium

Plutonium is an extremely complex material, critically important to the functioning of weapons. One of the major scientific challenges of the Stockpile Stewardship Program is comprehending the detailed properties of plutonium metal and alloys and how they age. Experiments at the Joint Actinide Shock Physics Experimental Research (JASPER) Facility and with diamond anvil cells are helping scientists better quantify properties of this material. Located at the Nevada Test Site, JASPER is a 30-meter-long, two-stage gas gun that accelerates a projectile to speeds of up to 8 kilometers per second.

In a JASPER experiment, the impact of the projectile produces an extremely high-pressure shock wave (about 600 gigapascals or 6 million atmospheres) in the targeted material, raising its temperature to as high as 7,000 kelvins. Through precise measurements of shock velocity, scientists are improving plutonium equation-of-state models used in weapon performance calculations. Although fewer tests were performed at JASPER than during the previous fiscal year, all experiments produced excellent data and several broke new ground. For example, researchers acquired the first simultaneous dynamic comparison data for aged versus unaged plutonium.

Laboratory experiments using diamond anvil cells complement shock physics experiments. A diamond anvil cell is a small mechanical press that squeezes a microgram of material between two small, flat-tipped diamonds, achieving pressures as high as 100 gigapascals. In diamond anvil experiments fielded at the Advanced Photon Source at Argonne National Laboratory and other synchrotron light sources, Livermore scientists obtained high-accuracy equation-of-state data for plutonium samples whose ages ranged from 0 to 45 years. Experimental data also characterized differences in equations of state among plutonium alloys and validated equation-of-state and phase-transition models.

Major Progress at the National Ignition Facility

Major progress continues to be made on the NIF project and preparing for fusion ignition experiments with the 192-beam laser. The NIF project is meeting all of its technical performance, cost, and schedule milestones. Current plans are to begin the first ignition experiments in fiscal year 2010. NIF's laser beams will compress fusion targets to the conditions required for thermonuclear burn, liberating more energy than is required to initiate the fusion reaction. Inertial confinement fusion energy is a long-standing program goal within DOE. NIF will offer researchers the capability to study physical processes at

The target chamber at the JASPER facility is specially designed to ensure that plutonium dust or fragments are not released into the environment after an experiment.

temperatures approaching 100 million degrees and 10 billion atmospheres, conditions that exist naturally only in the interior of stars and planets and in exploding nuclear weapons.

NIF is vital to the success of the Stockpile Stewardship Program. It is the only facility capable of creating, in the laboratory, the conditions necessary to experimentally study physical processes that occur during the nuclear phase of an exploding nuclear weapons. Data from precisely diagnosed experiments will elucidate key weapons performance issues and assist in validating physics models and numerical simulation codes. Over the coming decades, NIF experiments will also help train and rigorously test the capabilities of weapons scientists, on whom the nation depends to assess the safety, security, and performance of the U.S. stockpile.

In August 2005, two shots using eight laser beams achieved a record-setting 152 kilojoules of energy. With just its second "quad" of 192 beams commissioned, NIF produces more energy than the 60-beam OMEGA laser at the Laboratory for Laser Energetics at the University of Rochester, the next largest system. The combined output from the eight beams, referred to as a bundle, surpassed the Main Laser Operational Qualification goal of 125 kilojoules of infrared light per bundle. Beam quality, as well as total energy, exceeded design specifications. Before these shots took place, a newly designed automated computer shot control software dubbed HOTShots, or Hands Off Target Shots, began controlling all NIF shots.

The NIF project met another milestone in October with the installation of the 1,000th line replaceable unit (LRU). Weighing between 500 and 1,000 kilograms each, LRUs are complex modules containing instrumentation and optical components to amplify laser light as it passes through. There are over 20 different types of these precision electro-optical/mechanical structures. When completed, NIF will have more than 6,200 LRUs. Because

Workers are dwarfed by the final optics assemblies entering the 10-meter-diameter target chamber (top) at the National Ignition Facility (above).

modular LRUs can easily be removed and refurbished or upgraded, NIF will have less downtime and be easier to maintain over the long term. The LRUs are assembled and tested in the Optics Assembly Building, a cleanroom facility adjacent to NIF. The optical surfaces of LRU components need to be aligned to within a fraction of a millimeter. After technicians validate an LRU's alignment, cleanliness, and operation, the LRU is moved in a robotic portable cleanroom to one of the laser bays and inserted into a beamline.

NIF Looks Toward Ignition

The results of a series of four-beam NIF experiments, published in *Physical Review Letters*, indicate that NIF is on the right path to successfully achieving ignition. The experiments studied plasma conditions inside hohlraums, small cylinders that convert laser light to x rays. In future fusion experiments, x rays will cause the implosion of a tiny capsule inside the hohlraum to create fusion ignition. The four-beam experiments examined the hohlraum's radiation temperature and how rapidly plasma is produced. These data are important because laser energy delivered late in a long pulse (more than several nanoseconds) is ineffective for achieving ignition if the hohlraum is already filled with plasma.

Advanced diagnostics measured the x-ray spectra and radiation temperatures inside the hohlraum in experiments using various sizes of hohlraums and different laser pulse lengths. Instruments also imaged the x rays that were energetic enough to escape the hohlraum. The precise data gathered were then compared to the predictions of theoretical and detailed computational models, which proved to be remarkably accurate. These important findings confirm that the larger hohlraums to be used for NIF ignition experiments should create plasma slowly

NIF's 1,000th line-replacable optical unit is maneuvered into position.

enough to achieve the implosion conditions necessary for ignition.

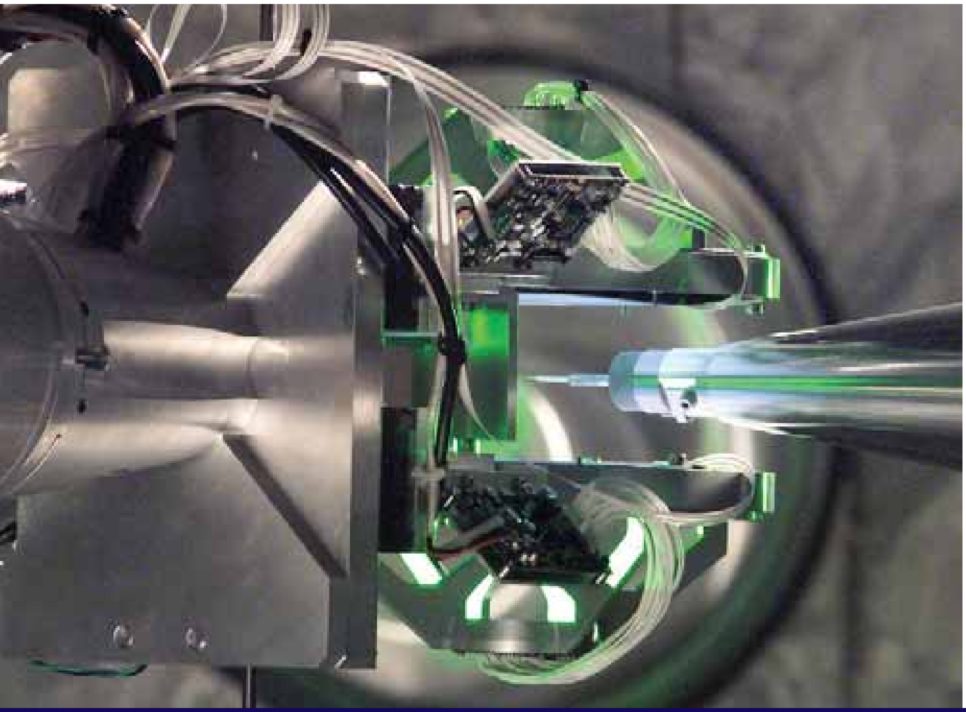
Planning for future ignition experiments at NIF is under way. Two workshops were held at Livermore in January and February 2005 to develop an integrated plan for achieving ignition and coordinating activities and responsibilities. Representatives from all laboratories participating in the ignition campaign attended the workshops. The resultant *National Ignition Campaign Execution Plan* was approved by NNSA in June. As mentioned, the plan calls for the first ignition experiments in fiscal year 2010. Ongoing experiments at OMEGA and other facilities are testing diagnostic concepts planned for NIF as well as alternative ideas for ignition target designs. At Livermore, good progress was made last year in the areas of target design, target fabrication, and advanced diagnostic development.

Planning for the Future

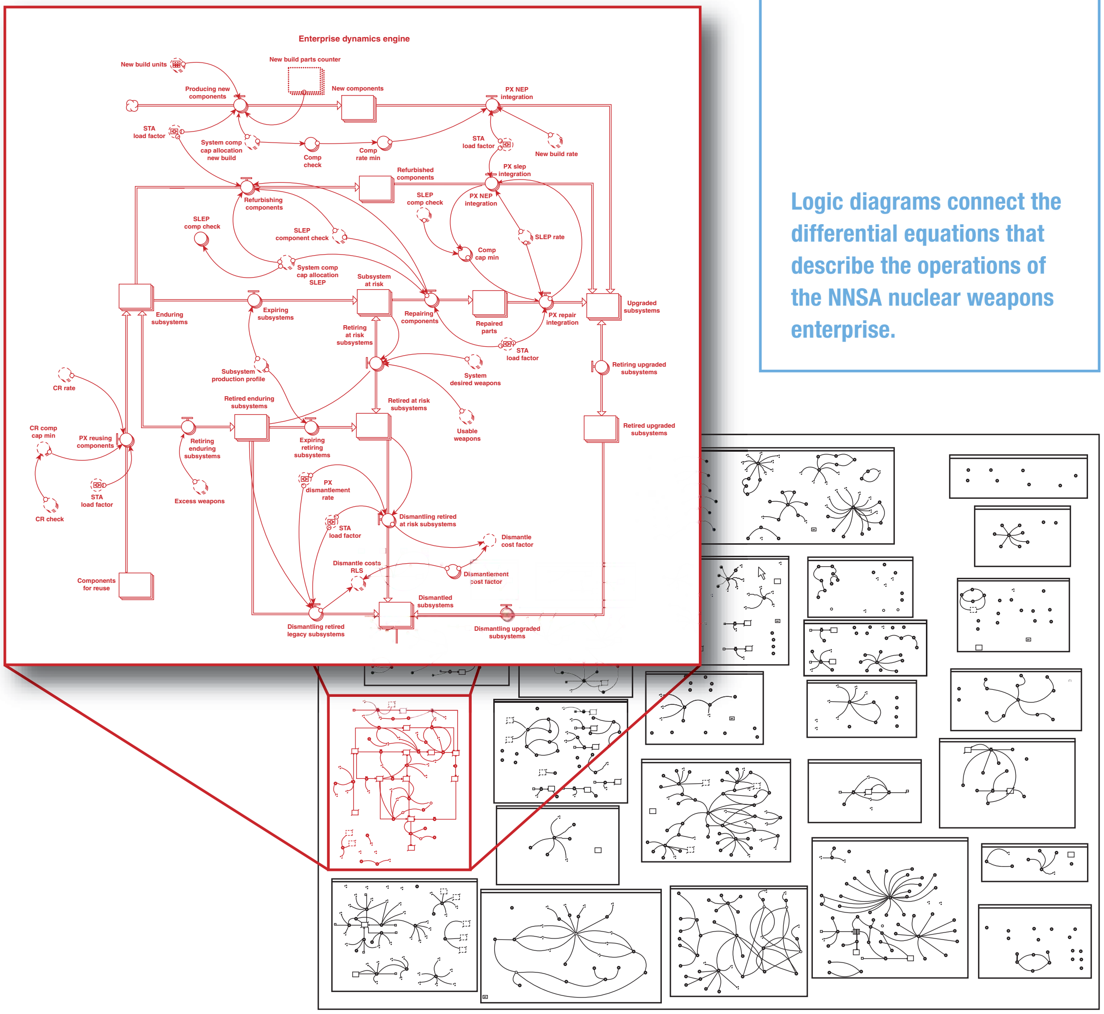
As the nation adapts to the security threats of the 21st century, the role of nuclear weapons is changing, and so must the large nuclear weapons complex, or enterprise. The nation is committed to maintaining a reliable, safe, and secure nuclear deterrent with the lowest possible number of weapons. However, NNSA's nuclear weapons enterprise has many large and aging facilities, and it must support legacy warhead designs well beyond their originally projected lifetimes. A series of top-level studies and reviews at DOE, NNSA, and the Department of Defense (DoD) has called for a smaller, more agile nuclear enterprise. It needs to be more cost efficient and able to respond quickly to sudden surprises, such as a major geopolitical change or the discovery of an acute technical problem in the nuclear stockpile.

The NNSA faces the challenge of making the transition to a smaller, more agile enterprise while also maintaining an aging stockpile. To help meet this challenge, a team of Livermore researchers has built a modeling tool for testing future enterprise strategies. The team combined differential equations with an enormous database of information to model in extreme detail how each facility in the enterprise functions. This detail is required because the NNSA enterprise is a highly nonlinear system; activities among the plants and laboratories are complicated and interdependent. Rigorous verification and validation serve to ensure that the new model appropriately reflects the workings of the enterprise.

The Livermore model represents the enterprise's flow of activities by incorporating accurate financial, production, warhead dismantlement, and stockpile data. The goal is for NNSA managers to see more clearly how policy decisions might affect the enterprise. They could then optimize the transition from the present infrastructure to a more responsive one while maintaining important stockpile commitments. The model has received high marks for thoroughness and utility from managers at DOE, NNSA, and many NNSA facilities. U.S. Strategic



Inside the target chamber, an alignment system is used to position a NIF target, which would be at the tip of the target positioning system entering from the right.



Logic diagrams connect the differential equations that describe the operations of the NNSA nuclear weapons enterprise.

Command and the Defense Threat Reduction Agency are collaborating with Livermore experts to develop a complementary model of the DoD's nuclear enterprise.

NNSA managers are considering a long-term approach for a sustainable nuclear weapons enterprise that would shift from a program of warhead refurbishment to one of warhead replacement. To better evaluate this proposal, NNSA began the Reliable Replacement Warhead (RRW) Program with support from Congress, and Livermore is an active participant. The program's goal is to determine the effectiveness of replacing existing warheads with ones manufactured from materials that are more readily available and more environmentally benign than those used in current designs. These modified warheads would be much less costly to manufacture, their designs would include advanced safety technology, and their safety and reliability would be easier to certify. Establishing a responsive nuclear infrastructure, together with the RRW Program, would make possible additional stockpile reductions.